THE CONTROL OF VARIOUS SPECIES OF STORED-PRODUCT INSECTS WITH EHF ENERGY

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The work reported here is ancillary to previous efforts by the authors to assess the effectiveness and economics of controlling stored-grain insects with microwave energy in the Extremely High Frequency (EHF) and Super High Frequency (SHF) range of the free-water relaxation band. This band was chosen because of the coincidence of free water in the insect and the availability of extremely high-power microwave oscillators in that range that makes continuous processing of a dynamic product at high throughput rates a realizable goal (Halverson et al. 1997, Plarre et al. 1997). Previous questions about the depth of penetration of energy into a mass of cereal grain and air mixtures flowing under gravitational forces have been answered and the volume ratios necessary to achieve full penetration of a product in a practicable applicator are known (Halverson et al. 1998). The bounding energy input per unit mass of infested product which would kill all species and age levels of selected major insect pests in cereal grains was determined here in order to assess the cost of energy to achieve an LD99 level of mortality.

The tests reported here were conducted on dynamic samples of hard red wheat, *Triticum aestivum* (L.), infested with pupae, young larvae and eggs of the rice weevil *Sitophilus oryzae* (L), the red flour beetle *Tribolium castaneum* (Herbst), and the lesser grain borer *Rhizopertha dominica* (F.). The microwave power source was a 200 kW, 28 GHz, gyrotron that delivered energy to an applicator developed previously to test small samples flowing at an instantaneous rate of 0.50 tonnes/h. The purpose was to determine which of the tested species and age level was the least susceptible to control by energy at the frequency chosen and to perform germination and milling and baking quality evaluations. The least vulnerable species and age level identified will be used in subsequent tests to determine upper energy and temperature bounds for a full scale prototype at ~24 tonnes/h. Tests were also conducted on the least vulnerable species and age level at constant energy input for various input power levels and exposure times to determine whether a minimum exposure time limit exists for the dynamic treatment. The cavity applicator used for the tests is described in Halverson et al. 1997.

Experimental Design.

For the tests to determine the least vulnerable species and age, three factors were controlled. These factors were input power: 6 levels (including zero for the controls), insect species: 3 (rice weevil, red flour beetle and lesser grain borer), and age group: 3 (egg, young larvae and pupae). Uninfested germination samples were also exposed at the 6 power levels. All factors except for power were randomized during the runs. Because of the difficulty in calibrating the gyrotron at each of the 5 energized levels the power levels were selected randomly but remained unchanged during a particular random run of infested samples, uninfested germination, and milling and baking samples. The measured average sample mass of the infested and germination samples was 170 g and average mass flowrate was 139.43 g/s yielding an average flow time of 1.251 s. Each sample was replicated three times. The exposure time period, determined by the time of flight of a single kernel between the two LEDs, was 539 ms. Three replications of uninfested samples used for the milling and baking quality studies at each power level had a measured mass of 720 g with an average flow time of 5.164 s.

For the tests at 28 GHz, to determine if a minimum exposure time exists within a range of 1 to 1/8 exposure time periods, the energy input to the sample was constant and therefore the 4 levels of exposure time were dependent upon the randomly chosen power level. The pulse length of the gyrotron during the sample flow time was then adjusted so that the power-exposure time product (energy) was constant. There were 3 replications of each sample.

Mortality.

For the dynamic test at 28 GHz plots of the mortality versus the energy delivered to the sample per unit mass in J/g and the maximum temperature for the least vulnerable species and age group was determined from a probit analysis of the data. The values of Uload at 50% and 99% mortality are given in Tables 1 and 2 respectively.

Table 1. Values of Uload (energy delivered to the sample per unit mass in J/g) at the 50 % level of mortality for rice weevil, red flour beetle and lesser grain borer pupae, young larvae and eggs. Values are determined by probit regression. Volume ratio (vg) = 0.67%,

Species	**Age**	**Uload J/g**	**Remarks**
Rice weevil	pupae	7.794	Most vulnerable
	young larvae	11.517	
	egg	11.528	
Red flour beetle	pupae	10.045	
	young larvae	18.825	
	egg	20.330	Least vulnerable
LGB	pupae	10.200	
	young larvae	12.011	
	egg	15.326	

Table 2 Values of Uload (energy delivered to the sample per unit mass in J/g) at the 99 % level of mortality for rice weevil, red flour beetle and lesser grain borer pupae, young larvae and eggs. Values are determined by probit regression. Volume ratio (vg) = 0.67%,

Species	**Age**	**Uload J/g**	**Remarks**
Rice weevil	pupae	17.643	Most vulnerable
	young larvae	26.295	
	egg	42.890	
Red flour beetle	pupae	33.050	
	young larvae	54.858	

	egg	48.454	
LGB	pupae	27.426	
	young larvae	36.532	
	egg	56.832	Least vulnerable, bounding case

From Tables 1 and 2 it is seen that the egg of the lesser grain borer is the least vulnerable of the species tested. In general both the young larvae and eggs of all species were less vulnerable than the pupae. This may be due to decreased radiation coupling caused by the much smaller physical size and energy-absorbing cross section and the shielding effects of the product in which the young larvae and egg reside. The major mechanism of energy transfer in those cases is probably thermal conduction, which is a much slower process than radiation. Nevertheless exposure times of 539 ms were sufficiently long to kill the larvae and eggs but required greater energy input to do so. The results of this test are consistent with results of earlier tests on similar age stages of the maize weevil *Sitophilus zeamais* (Motschulsky) reported in Halverson et al. 1997.

No comparable data are available in the open literature at frequencies in the bound water relaxation band (10 to 100 MHz) for these species and age levels to confirm the relative effectiveness of operating in the free water band. However, a comparison of the mortality vs. temperature plots with the 1 d adult rice weevil mortality versus temperature plots of Nelson and Stetson 1974 with that of the emergence of adults from the pupal age stage at 14 d indicate that the mortality of pupae of the rice weevil at 28 GHz is greater than that of the adults at 39 MHz. This is a significant indicator since the adults are known to be the most vulnerable age stage.

Germination and milling and baking qualities

Germination of the exposed seeds ranged between 90 and 100 %. Percentage germination correlated negatively with the rise in temperature of irradiated seeds and U load (J/g, $r \geq -0.6062$) at increased input power levels. The values appeared to be significant because of the low variation. Plots of the germination data yielded the following linear equations over the Uload range of 0 to 73.08 J/g and ΔT range of 0 to 41.4 °C.

Germination % = -0.0876(Uload) + 96.588

Germination % = $-0.1634(\Delta T) + 96.816$

The effects on both germination and milling and baking qualities were not economically significant.

Estimated Cost of treatment

A complete determination of the cost of treatment of stored products per unit product at the specific frequency studied here was not undertaken since it requires the technical specification of a complete system, including auxiliary systems, and the determination of capital, fixed and operating costs. However, the cost of electrical energy component of the operating costs to treat the product at a rate of 24 tonnes/h may be determined from equation (2) of Halverson et al. 1996 using the bounding value of Uload for the lesser grain borer eggs . With a 200 kW gyrotron operating at 50% efficiency, a coupling factor (k) of 50%, and a busbar cost of $0.02 / kW-h, the total cost of electrical energy is $0.67/tonne. The busbar cost used is considered reasonable for industrial use under deregulated utility conditions. It is estimated that the capital, fixed and operating costs may increase the total cost to $0.97/tonne.

A comparison of the above estimated cost with costs predicted in Nelson, 1996 for a 200 kW High Frequency (HF) system indicates that the estimated treatment rate at frequencies at or near the bound water relaxation band (10 to100 MHz) is only one-half that of a 28 GHz system. The cost per unit product was given as $ 1.29/tonne including depreciation costs and certain fixed and operating costs. The estimate did not consider the effect of the coupling factor on the reduction of the overall efficiency nor the energy required to kill the least vulnerable species and age level. This would increase the total estimated cost.

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